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Stratiform Barite Deposits in the Roberts Mountains Allochthon, Nevada: A Review of Potential Analogs in Modern Sea-Floor Environments

Chapter H of

Contributions to Industrial-Minerals Research

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Stratiform Barite Deposits in the Roberts Mountains Allochthon, Nevada: A Review of Potential Analogs in Modern Sea-Floor Environments

Abstract

The United States is a net importer of barite, a critical mineral for the oil and gas industry; more than 80 percent of current domestic consumption of barite is imported from China. Nearly all of the domestic production of barite comes from stratiform deposits in Nevada. The "modern analogs" approach adopted in this review can contribute to improving deposit models and the long-term resource picture in the United States.

Massive barite deposits in Nevada are interlayered with deep-water siliceous sedimentary strata of Paleozoic age within the Roberts Mountains Allochthon. Although the barite deposits formed along the long-lived, tectonically active margin of western North America before the Antler orogeny, uncertainty still exists regarding key aspects of their genesis, especially with respect to tectonic setting and depositional processes. Proposed tectonic settings include a continental slope adjacent to an ocean basin, and a rifted basin formed on continental crust. A margin dominated by other stress configurations and strike-slip faulting may also have been present during the Paleozoic. Hypotheses for the genesis of sediment-hosted, stratiform barite deposits in Nevada can be grouped into two categories: (1) a synsedimentary hydrothermal model and (2) an ocean-circulation/productivity-zone model. Both models include a stage involving bacterial reduction of seawater sulfate.

Disseminated, diagenetic, and hydrothermal barite deposits are widespread features of the modern ocean. In the Pacific Ocean, disseminated barite deposits (max 9 weight percent $BaSO_4$) are forming below high-productivity zones (for example, in equatorial belts) and on the flanks of ocean ridges (as fallout of "black smoker" particles). Massive barite deposits of diagenetic (in the subsea floor and at cold seeps) and hydrothermal origins are present in several sediment-covered tectonic settings, including ocean ridges (Escanaba Trough and Guaymas Basin), oceanic transform faults (Blanco Fracture Zone), marginal basins (Sea of Okhotsk), convergent margins (Peru, Oregon, Alaska), and transform margins (California Continental Borderland). Both hydrothermal and diagenetic barite deposits may be present in some environments (for example, the California California Borderland).

On the basis of a consideration of tectonic settings and a comparison of deposit attributes (associated rock types, size, structure), mineralogy ($BaSO_4$ content, SiO_2 content), and geochemistry (S- and Sr-isotopic ratios) for modern and ancient massive barite deposits, cold seeps along transform margins (or, possibly, marginal basins) represent the most promising present-day metallogenetic analogs for stratiform barite. Hydrothermal systems can also produce high-grade barite, but the ubiquity of associated sulfide mineralization on the modern sea floor (and the paucity of sulfides in Nevada deposits) is problematic. On the basis of data from modern barite deposits, the presence of vent-specific faunas (tubeworms) and the variation in $\delta^{34}S$ values for barite (related to bacterial reduction of seawater sulfate) may not permit discrimination between a diagenetic or hydrothermal origin for ancient barite deposits.

Introduction

Barite ($BaSO_4$) is a critically important mineral for the energy industry. Since 1975, about 90 percent of the barite consumed worldwide has been used in the oil and gas industry. In 2001, 95 percent of the barite produced and sold in the United States was used as a weighting agent in gas- and oil-well-drilling fluids. The estimated U.S. consumption of barite in 2001 was 2.96 million t, of which 2.7 million t was imported; between 1997 and 2002, 86 percent of imported barite came from China (Searls, 2003). In the decades ahead, the barite market will continue to be governed by oil- and gas-drilling activity (Bearden, 1997). The increasing U.S. energy demand, coupled with renewed emphasis on domestic production, should result in increased domestic oil and gas exploration both onshore and offshore. An increasing demand for natural gas, for example, will require a doubling of the number of gas wells drilled annually by the year 2020 (Anonymous, 2001). Thus, the national need for barite and other energy-related industrial commodities is expected to rise commensurately.

Most of the barite mined in the United States comes from Nevada. As a result, the United States is the third-largest producer of barite in the world, after China and India. Approximately 435,000 t of barite was shipped from three Nevada mines in 2000; considerably smaller amounts were mined in Georgia and Tennessee (Searls, 2000). High overland-shipping costs for processed barite ore have led to a decline in U.S. production, especially for barite produced at the Nevada sites, which are distant from markets in North America. Current U.S. reserves of barite are approximately 26 million t (Searls, 2003).

Barite mined in Nevada is recovered from stratiform deposits in the Roberts Mountains Allochthon, a well-defined northeast-trending belt of sedimentary and volcanic rocks of Paleozoic age; more than 120 individual deposits are known (fig. 1; Papke, 1984). The deposits are widely distributed as conformable layers and lenses of massive barite interbedded with predominantly siliceous sedimentary strata, most notably chert.

Although sedimentary barite deposits in Nevada and elsewhere have been the focus of considerable research (for example, Hanor, 2002), uncertainty still exists regarding key aspects of their genesis, especially tectonic setting and mineral-forming processes. Although the tectonic setting is generally characterized as "continental margin," little agreement exists regarding the details of plate interaction or faulting that promoted barite mineralization. With respect to mineral-forming processes, two general hypotheses have been proposed: (1) a synsedimentary hydrothermal model and (2) an ocean-circulation/productivity-zone model. Both of these process-oriented models are consistent with the distribution of deposits within a continental-margin setting.

Recent discoveries of barite deposits forming in diverse submarine environments of tectonically active continental margins can shed light on the origins of the stratiform deposits found in the geologic record. Sediment-floored, continental-margin settings that host massive barite mineralization include ocean ridges, rifted continental margins, marginal basins, transform margins, and trench-slope environments of convergent margins. In this chapter, we adopt a "modern analogs" approach—a consideration of the tectonic setting and geochemical characteristics of sea-floor barite deposits—to enhance our understanding of the occurrence and genesis of Paleozoic stratiform barite deposits in Nevada and elsewhere in the North American Cordillera. In following this approach, we make no prior assumption that an unequivocal modern analog exists in any strict sense. This chapter, therefore, represents a starting point. Our ultimate goal is improved deposit models that can contribute to the long-term barite resource picture in the United States. In addition, new insights into barite metallogenesis may be applied to other types of mineral deposits formed in continental-margin settings (for example, gold, phosphorite).

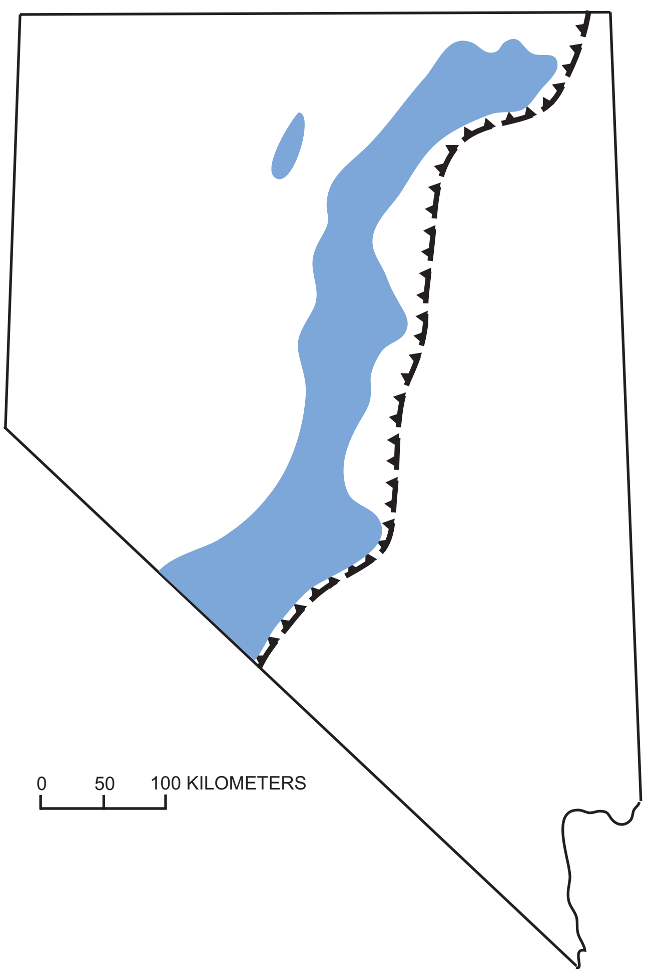

Figure 1.—Sketch map of Nevada, showing distribution of massive barite deposits (blue areas) within the Roberts Mountains Allochthon (after Papke, 1984). Eastern margin of the allochthon is marked by thrust-fault pattern, with teeth on upper plate.

Stratiform Barite Deposits of Nevada

Regional Geology

Stratiform barite deposits in Nevada are concordant within siliceous sedimentary strata of the Roberts Mountains Allochthon, an assemblage of deformed Cambrian through Devonian eugeoclinal strata extending from southeastern California northeastward across Nevada into Idaho (fig. 1). These displaced and deformed rocks were thrust as much as 200 km eastward over carbonate-shelf rocks of the adjacent continental margin along the Roberts Mountains thrust during the Antler orogeny in Late Devonian through Early Mississippian time (Roberts and others, 1958; Johnson and Pendergast, 1981; Madrid and others, 1992).

Sedimentary- and volcanic-rock types within the Roberts Mountains Allochthon include chert, shale, argillite, quartzite, quartz- and feldspar-rich sandstone, basalt, limestone, siliceous carbonates, and phosphorite. This lithologic association is generally considered to represent both hemipelagic and turbiditic deposition within a spectrum of continental rise, slope, and basin environments during the evolution from a passive to an active margin (Madrid and others, 1992; Finney and others, 1993). During the Antler orogeny, these rocks were stacked in a sequence of nappes, resulting in an older-over-younger stratigraphy. Stratiform barite deposits are most abundant in Ordovician and Devonian sedimentary rocks but also occur in rocks of Cambrian and Silurian age (Poole, 1988). Dubé (1988) reported a Famennian age (Late Devonian) for brachiopods in barite and similar ages for radiolarians in chert from several districts in the Roberts Mountains Allochthon.

Deposit Characteristics

Detailed geologic descriptions of Nevada barite deposits are presented in numerous publications (for example, Shawe and others, 1969; Papke, 1984; Dubé, 1988; Poole, 1988), and so only a brief summary is given here and in table 1. Individual barite beds typically are 0.3 to 15 m thick (fig. 2*A*), but aggregate thicknesses (excluding thin interbeds of chert or shale) may exceed 25 m (Papke, 1984). Maximum strike lengths for individual barite beds are about 100 m but for thicker aggregate deposits may exceed 300 m. Barite deposits are closely associated with bedded radiolarian chert (fig. 2*B*) and, to a lesser extent, with shale and argillite, which occur as thin interbeds in both barite and chert. Less common sedimentary-rock types that occur in barite deposits include limestone, siltstone, and conglomerate containing chert or barite fragments. In places, massive and clastic barite beds are interstratified. Although igneous rocks are generally a minor component of the Roberts Mountains Allochthon, greenstone (alkalic basalt) and lamprophyre dikes are present in some districts (Dubé, 1988; Madrid and others, 1992). Deposits pinch out against other rock types or are terminated by syndepositional high-angle faults.

Within deposits, massive saccharoidal and laminated barite are most abundant (fig. 2). Poole (1988) listed three other types of stratiform barite: dense concentrations of spheroidal masses (rosettes) in beds of fine-grained barite, chert, and shale; barite conglomerate and sandstone; and barite cement in sandstone and siltstone.

Quartz is ubiquitous in laminated and spheroidal barite beds, whereas calcite, pyrite, witherite, and celestite are reported in only a few deposits (Papke, 1984). Organic matter, which is a major impurity (several weight percent) in both bedded barite and associated chert, is mostly marine sapropel (Poole and Claypool, 1984). Phosphatic nodules and lenses occur in laminated and rosette barite, as well as in associated chert beds, in the Toquima Range (Rye and others, 1978; Graber and Chafetz, 1990; Coles, 1996). According to Papke (1984), powdery masses of Fe and Mn oxides, as well as Fe-rich gossans derived from sulfide oxidation, occur in about 25 and 33 percent of the deposits, respectively. These small oxide-rich bodies are generally oriented parallel to bedding. We note, however, that massive sulfide deposits are not spatially associated with stratiform barite mineralization in Nevada.

An important discovery with relevance to the genesis of barite deposits is the preservation in barite beds of fossil brachiopod shells and tubeworms (fig. 2*D*) that appear to represent macrofaunas endemic to fluid ventsites on the sea floor during periods of barite deposition (Dubé, 1988; Poole, 1988).

Regional Tectonic Models for the Roberts Mountains Allochthon

The depositional history and tectonic setting for sedimentary rocks of the Roberts Mountains Allochthon have been widely debated, and detailed studies of barite deposits have contributed to the debate. Most workers believe that the sedimentary strata of the allochthon (including stratiform barite deposits) represent a deep-water marine assemblage deposited within a long-lived, tectonically active zone outboard (westward) of the continental shelf. This tectonically active continental margin may have existed for a period of 135–180 m.y. before the Antler orogeny (Madrid and others, 1992). The Late Devonian (Famennian) age of interbedded barite and chert deposits (for example, in the Toquima Range; Dubé, 1988) suggests that some barite mineralization in outer-continental-margin environments was synchronous with the earliest stages of Antler-style tectonism and initial eastward emplacement of the Roberts Mountains Allochthon over miogeoclinal-shelf rocks.

Two proposed tectonic settings for sedimentation and barite deposition in the Roberts Mountains Allochthon are illustrated in figure 3. In the first model (fig. 3*A*), organic- and silica-rich sedimentary strata and barite deposits formed on the outer edge of a passive continental margin, outboard of the continental shelf underlain by carbonate rocks to the east and inboard of a narrow ocean basin and a volcanic arc to the west (Maynard and Okita, 1991). The volcanic arc is underlain by a west-dipping subduction zone. According to this interpretation, the sedimentary strata and barite deposits were emplaced eastward onto the continental margin during plate convergence and closure of the ocean basin in Late Devonian time.

In the second model (fig. 3*B*), sedimentation occurred in rift basins formed on continental crust (Turner and others, 1989; Madrid and others, 1992; Finney and others, 1993). Similar epicontinental rifts are the proposed settings for stratiform Pb-Zn sulfide±barite (sedex) deposits of Paleozoic age in the Canadian Cordillera (Goodfellow and others, 1993). In this model, detritus entering the basins from terrestrial sources to the east mixed with sand from emergent highlands to the west. The barite-chert-phosphorite association developed during periods of minimal clastic sedimentation in the rift basins. The occurrence of alkaline basalt records multiple episodes of extension and attenuation of continental crust during Middle Cambrian through Late Devonian time (Madrid and others, 1992). Evidence for the formation of true oceanic crust in these marginal basins is absent; however, scattered tectonized ultramafic bodies in the allochthon may represent displaced pieces of asthenosphere (Poole and Desborough, 1973).

Sedimentary basins may have formed under other stress configurations in a long-lived complex margin. For example, analysis of the distribution patterns of Proterozoic rocks in the northern Canadian Cordillera led Eisbacher (1983) to propose that much of the western North American continental margin during the Middle Paleozoic was dominated by sinistral faulting. In that type of setting, pullapart basins could have formed by transtensional faulting. Furthermore, Dubé (1988) suggested that lamprophyric intrusions in the allochthon may represent igneous activity during extension in a transform setting.

Although compositional variations in clastic sedimentary units in the Roberts Mountains Allochthon led to suggestions that the assemblage is an exotic terrane (Coney and others, 1980; Schweickert and Snyder, 1981), analyses of stratigraphic relations across the allochthon and recent U-Pb data for detrital zircons from sandstone units in the allochthon indicate that detrital sources were exclusive to the North American craton (Madrid, 1992; Gehrels and others, 2000).

Depositional Models for Stratiform Barite

Hypotheses for the genesis of sediment-hosted, stratiform barite deposits in Nevada fall into two distinct categories: (1) formation by synsedimentary hydrothermal processes (Papke, 1984; Murchey and others, 1987; Dubé, 1988; Poole, 1988; Maynard and Okita, 1991) and (2) formation in zones of ocean upwelling and high productivity (Graber and Chafetz, 1990; Jewell and Stallard, 1991; Jewell, 1994, 2000). Evidence cited in support of a synsedimentary hydrothermal origin for Nevada barite deposits includes S- and O-isotopic characteristics, lensoid deposits spatially associated with synsedimentary block faulting, local Mn-rich zones and Fe-rich gossans, association with mafic volcanic rocks, and the presence of such

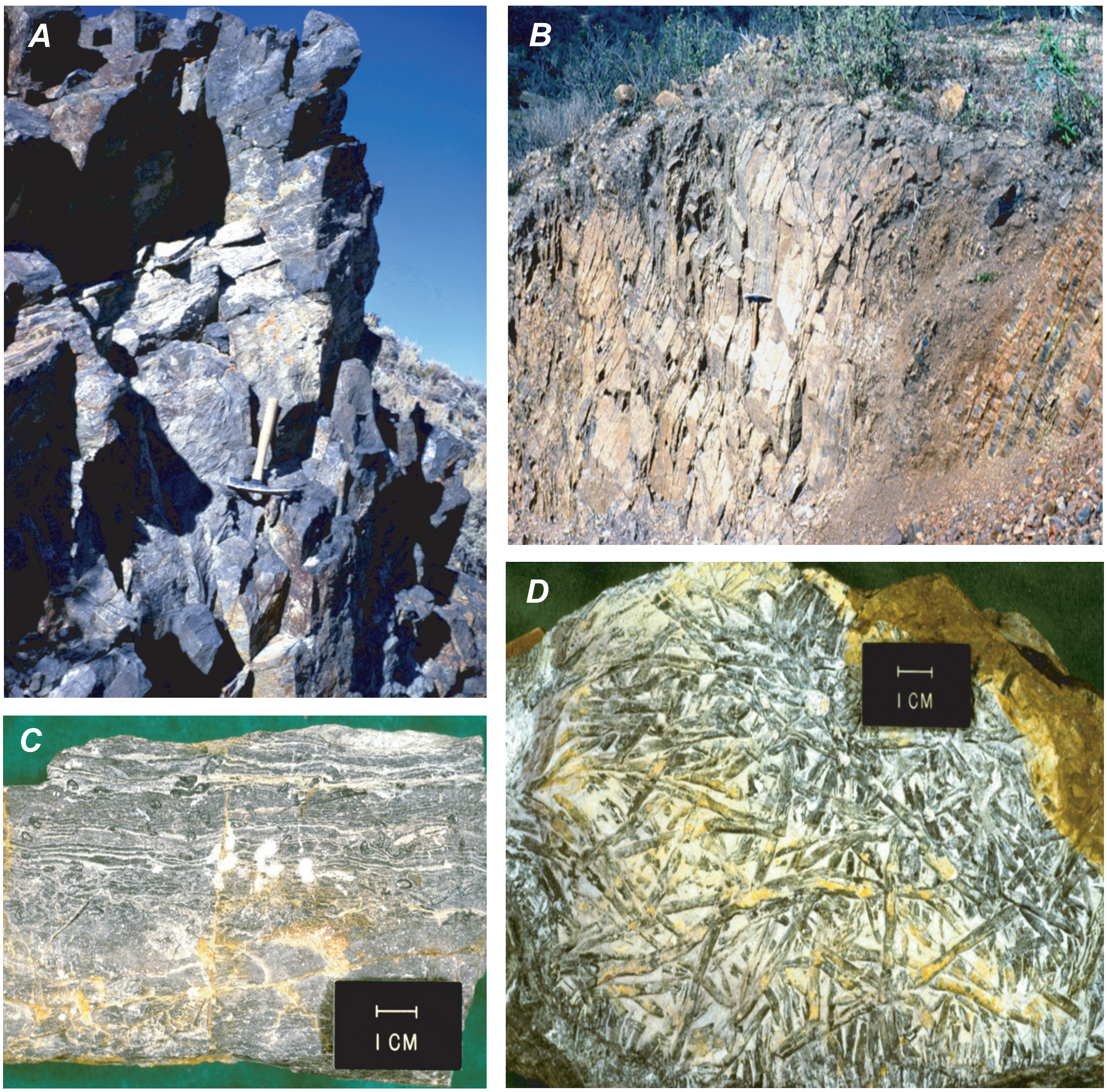

Figure 2.—Characteristics of massive barite deposits. *A*, Massive barite bed within the Slaven Chert, eastern Northumberland Canyon, Nev. *B*, Trench exposing steeply dipping, bedded barite (gray) and chert (reddish brown) in the Upper Devonian Los Pozos Formation, central Sonora, Mexico. *C*, Sample of massive to thinly laminated barite from the Slaven Chert, Queen Lode Mine, Nev. Darker laminae are enriched in organic matter. *D*, Dense cluster of tubeworms in barite deposit within the Slaven Chert. Photographs courtesy of F.G. Poole.

chemosynthetic vent fauna as bivalves and tubeworms. Indirect evidence is the spatial and temporal association of bedded barite deposits with sedex Pb-Zn deposits in Paleozoic strata of the Canadian Cordillera (Goodfellow and others, 1993).

A synsedimentary hydrothermal or "exhalative" model for the formation of hydrothermal barite deposits is illustrated in figure 4*A*. In this model, barium is leached from the underlying sediment by circulating, reduced brines and is transported along synsedimentary normal faults to the sea floor, where mixing of the brines with seawater induces precipitation of barite. Although many S-isotopic ratios for samples of bedded barite from Nevada are similar to those of Middle Paleozoic seawater sulfate ($\delta^{34}S$=~25 permil), higher ratios (max 56 permil) for barite rosettes and concretions indicate that anaero-

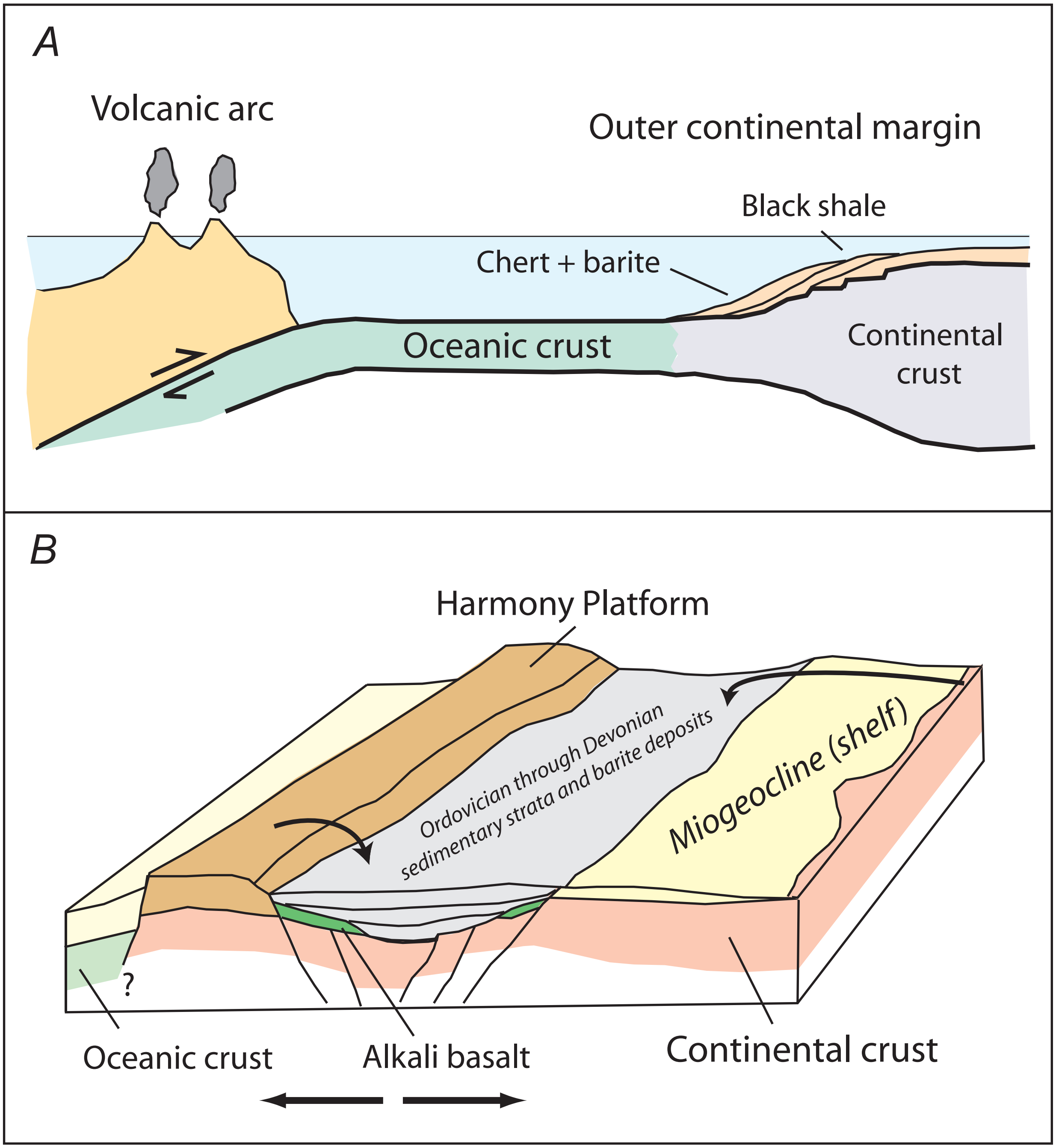

Figure 3.—Schematic models for barite deposition in Paleozoic continental-margin settings. *A*, Barite is deposited along with chert and black shale on outer continental margin, with a narrow ocean basin and island-arc assemblage to the west. Modified from Maynard and Okita (1991). *B*, Barite is deposited within rifted continental margin underlain by sediment derived from continental shelf to the east and an elevated platform to the west. Alkalic basalt represents occasional periods of extension and magmatism within basin. Curved arrows denote sediment transport; straight arrows denote extension of continental margin. Modified from Madrid and others (1992).

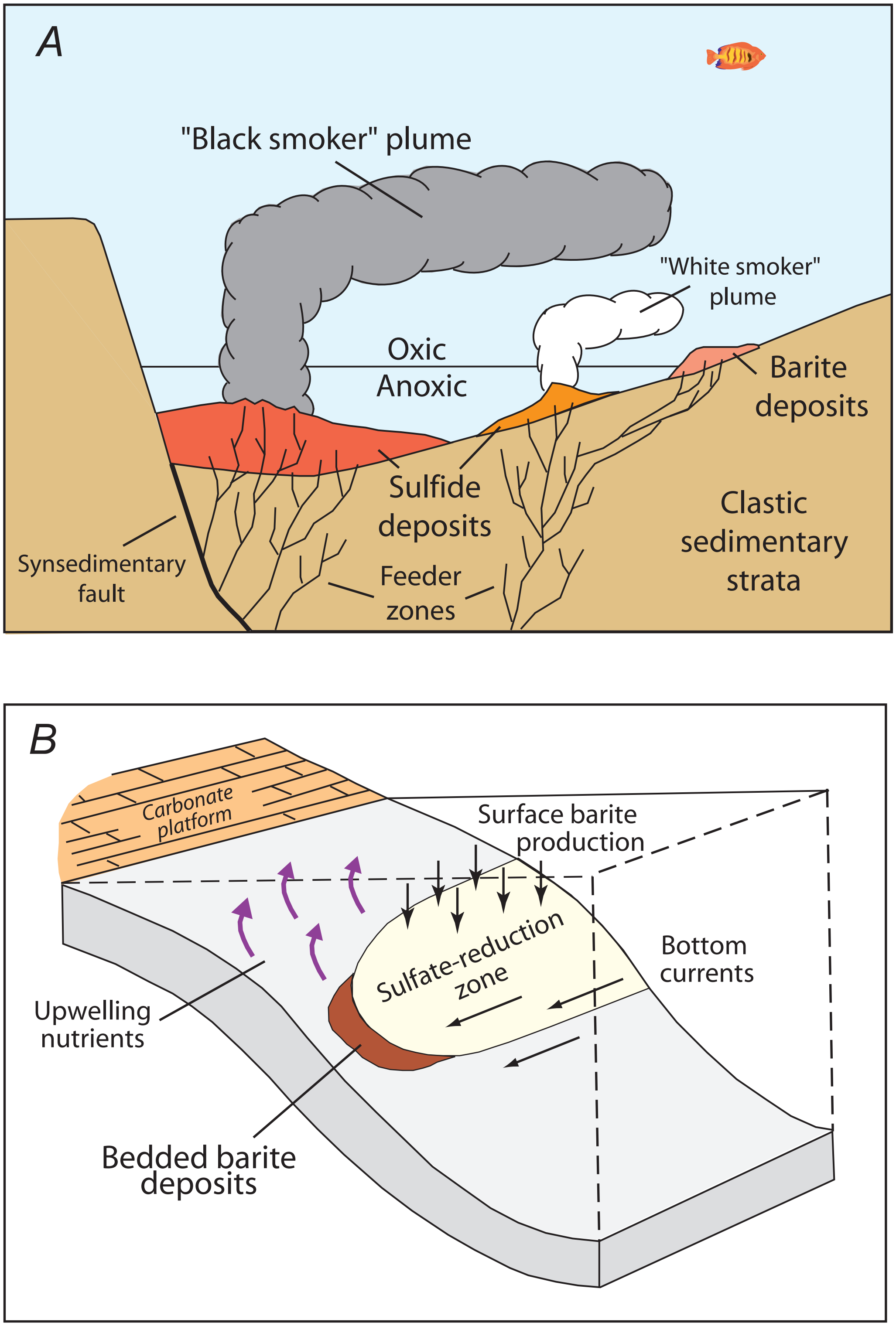

Figure 4.—Two process-oriented models for deposition of massive barite deposits. *A*, Hydrothermal model, in which thermal activity within a stratified basin results in proximal massive sulfide and distal massive barite deposits. Dissolved barium from hydrothermal vent fluids is concentrated in anoxic bottom waters. Barite deposits form where boundary between reduced, H_2S-bearing anoxic layer and oxic, sulfate-rich seawater intersects basin margins. Source of barium in this model is underlying sedimentary rocks or continental crust. Modified from Hanor and Baria (1977). *B*, Productivity-stratified ocean model, in which upwelling along continental margin results in high productivity and barite crystallization in decaying organic matter settling to ocean floor. Barite dissolves in anoxic bottom waters and reprecipitates at the oxic/anoxic-water boundary. Source of barium in this model is seawater. Modified from Jewell and Stallard (1991) and Jewell (1994).

bic reduction of seawater sulfate by bacteria in a closed system must have played a role in barite mineralization on the sea floor (Rye and others, 1978). The S-isotopic characteristics of barite and the occurrence of massive barite in organic-rich sedimentary sections are consistent with hydrothermal deposition in anoxic oceanic environments (Turner, 1992b; Poole and Emsbo, 2000). The formation of sulfide deposits in this model is hypothetical for Nevada barite deposits but is consistent with the relation of stratiform barite to Pb-Zn sulfide deposits in the Canadian Cordillera (Goodfellow and others, 1993).

An origin for Nevada barite deposits related to ocean circulation, upwelling, and high productivity is based on $^{87}Sr/^{86}Sr$ ratios, high P and organic-C contents, the presence of phosphatic nodules, and the abundance of microfossils in barite deposits and associated sedimentary strata (for example, the Slaven Chert). The appropriate conditions for barite mineralization are fostered by coastal upwelling of oxygen-depleted and nutrient-enriched seawater at topographically steep segments of continental-margin basins (fig. 4*B*). The resulting "rain" of abundant planktonic debris causes barite to precipitate in the upper part of the water column (Bishop, 1988). The barite then dissolves in sulfate-reducing bottom waters and reprecipitates where the bottom waters mix with normal sulfate-rich seawater. The modern Andean margin of South America is cited as a potential contemporary analog for these "biological precipitates" (Jewell, 2000). In this model, the source of barium is seawater, and the ore fluid is modified seawater that contains no hydrothermal component.

Modern Ocean-Floor Barite Deposits

Barite mineralization occurs in various tectonic settings on the ocean floor. Deposits in sedimentary environments can be subdivided into disseminated, diagenetic, and hydrothermal types on the basis of various physical and chemical attributes (table 1). The locations of known diagenetic and hydrothermal barite deposits are shown in figure 5.

Disseminated Barite

In modern ocean basins, barite is widely disseminated in sediment and is a minor but ubiquitous particulate phase in the water column (Church, 1979; Dehairs and others, 1980). The modern oceans, as a whole, are undersaturated with respect to barite (Church and Wolgemuth, 1972), although saturation conditions exist regionally in the surface, intermediate, and deep waters of some oceans (Monnin and others, 1999). The $BaSO_4$ content of deep-sea sediment is positively related to strong upwelling and high productivity (fig. 6). High-latitude regions, the equatorial zone, and continental margins of the Pacific Ocean contain anomalous concentrations of barite. The $BaSO_4$ content of biosiliceous sediment in continental-margin and high-latitude regions and of biocarbonate sediment in equatorial regions may reach 9 weight percent on an opal- or carbonate-free basis (table 1; Arrhenius and Bonatti, 1965). Fossil deposits of low-grade disseminated barite occur in many continental-margin sequences in the geologic record in which a history of upwelling is also evident (Stamatakis and Hein, 1993).

Although the specific mechanism for barite precipitation in the water column of high-productivity zones has not yet been determined, Dehairs and others (1980) and Bishop (1988) proposed that barite is formed in microenvironments within the upper part of the water column which contain decaying organic matter. More recently, Bertram and Cowen (1997) identified three morphologic types of barite (ovoid, hexagonal, and microcrystalline) in the surface oceans and suggested that precipitation occurred by both biogenic and abiogenic processes. The most abundant form of barite related to upwelling, referred to by many workers as "marine barite," is characterized by small grain size (<5 µm), an ellipsoidal morphology similar to the ovoid type of Bertram and Cowen (1997), and present-day seawater Sr- and S-isotopic ratios (Paytan and others, 1993, 2002).

The vigorous hydrothermal systems and buoyant plumes along oceanic spreading axes are another source of barite in sediment. Well-crystallized barite particles have been identified as a minor constituent of "black smoker" vent fluids emanating from the Juan de Fuca Ridge and the East Pacific Rise (Feely and others, 1987; Mottl and McConachy, 1990), and barite particles have been recovered from distal vent plumes 2 km from active discharge sites (Dymond and Roth, 1988). Bostrom and others (1973) and Dymond (1981) demonstrated that deep-sea sediment on the flanks of the East Pacific Rise and in the adjacent Bauer Deep are enriched in Ba to about 7 weight percent on a carbonate-free basis. Sediment near ocean ridges probably contains plume-derived barite, as well as barite derived from biogenic and hydrogenous sources. Barite crystals collected from hydrothermal plumes are coarser (20–70 µm) than those of other marine barites, and have well-formed bladed or rosette morphologies (Feely and others, 1987; Paytan and others, 2002). Plume barite crystals have Sr-isotopic ratios between those for contemporaneous seawater sulfate and basaltic Sr-isotopic ratios, whereas S-isotopic ratios are either comparable to seawater sulfate or slightly lower owing to the presence of reduced sulfur of hydrothermal origin (Paytan and others, 2002).

Diagenetic Barite Deposits

Diagenetic barite deposits form just beneath the sea floor, on the ocean floor at the margins of sulfate-reducing zones in bottom waters, and on the ocean floor in areas of cold-seep exhalations (fig. 5; table 1).

Subsurface Deposits Related to Zones of Sulfate Reduction

After burial, disseminated barite from the water column dissolves (or partially dissolves) during bacterial sulfate

Table 1.—Setting and characteristics of barite deposits in Nevada and on the modern sea floor.

[Data for Nevada deposits from Rye and others (1978), Papke (1984), Poole (1988), and Maynard and others (1995); data for sea-floor deposits from Feely and others (1987), Peter and Scott (1991), Peter and Shanks (1992), Dia and others (1993), Goodfellow and Franklin (1993), Zierenberg and others (1993), Fu and others (1994), Koski and others (1994), Torres and others (1996a, b, 2002), Aquilina and others (1997), Bertram and Cowen (1997), Naehr and others (2000), Greinert and others (2002), Hein (2002), and Paytan and others (2002). N.d., no data; SW, seawater]

Characteristic	Nevada deposits	Sea-floor deposits			
		Disseminated	Diagenetic, subsurface	Diagenetic, cold seep	Hydrothermal
Tectonic setting	Active continental margin	Flanks of ocean ridges, high latitudes, and equatorial belts.	Convergent margins	Convergent and transform margins, marginal basins, and passive margins.	Ocean ridges near or intersecting continental margins, and transform margins.
$BaSO_4$ content (in weight percent); other minerals.	>90; quartz, mica, calcite, pyrite	<10; siliceous sediment	10-50, max 80 in small deposits; siliceous.	>90; trace pyrite.	<50–>90; sulfides, silica, manganese oxide.
Crystal size and form	Individual crystals, max 1 mm across; microcrystalline to spheroidal, rosette.	<100 µm, ovoid or microcrystalline (biogenic); euhedral (hydrothermal).	<1 mm, needles, bladed, tabular.	20–700 µm; bladed, rosette.	Coarse grained (max 2 cm diam), euhedral, rosette.
Sr content in barite (in weight percent).	Max 0.5	Max 18 (ovoid)	n.d.	.5-11	Max ~3
$\delta^{34}S$ value of barite relative to SW.	SW to >SW	SW	>SW to >>SW	>SW	SW to >>SW
$^{87}Sr/^{86}Sr$ ratio of barite relative to SW.	SW to >SW	SW	>SW	<SW to >SW	<SW
Associated megafauna?	Yes	No	No	Yes	Yes

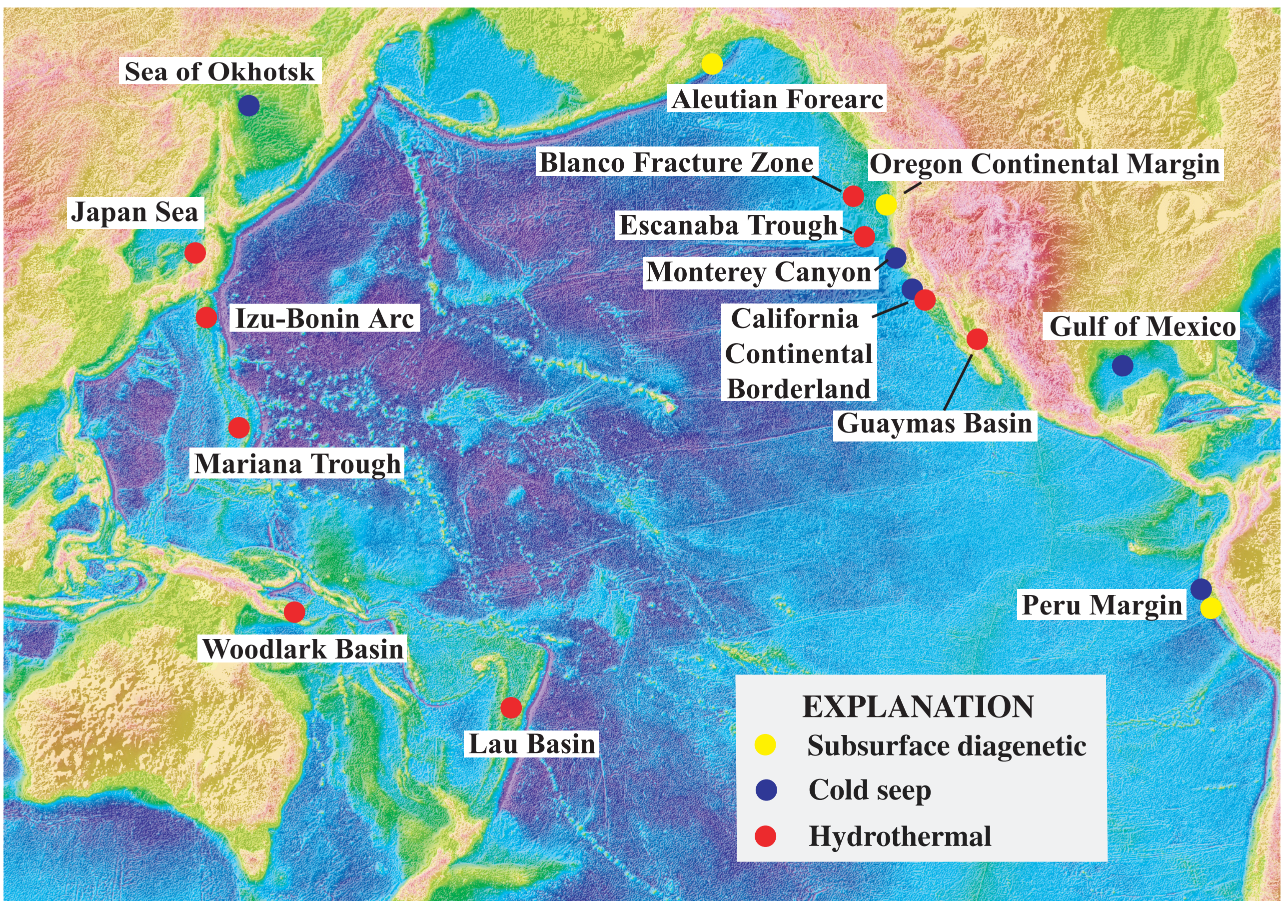

Figure 5.—Relief map of the Pacific Ocean, showing locations of diagenetic (subsurface and cold seep) and hydrothermal barite deposits. Locations of diagenetic sites from Dia and others (1993), Torres and others (1996a, b, 2002), Aquilina and others (1997), Naehr and others (2000), and Greinert and others (2002); locations of hydrothermal sites from Koski and others (1988), Peter and Scott (1988), Moore and Stakes (1990), Urabe and Kusakabe (1990), Binns and others (1993), Astakhova and Mel'nichenko (2002), and Hein (2002). Locations of deposits in passive-margin setting of the Gulf of Mexico (Fu and others, 1994) are also shown. Only deposits in sediment-floored environments of the Pacific rim are described in text.

reduction. The breakdown of barite and the consequent release of barium into ambient pore water are linked to the anaerobic degradation of organic matter in the sediment. Additional barium in pore water is supplied from decaying organic matter, and barium may also be derived from interaction of circulating fluids with basalt and other crustal rocks at depth. Barite is redeposited along diagenetic fronts at which reduced fluids mix with oxic pore waters in the subsurface or with oxygenated seawater at the sea-floor/seawater interface (fig. 7; Torres and others, 1996a). The migration of Ba-rich fluids can result from compaction, seismic activity, sudden mass-wasting events, and advection of subsurface brines. All of these processes are common in areas of strong oceanic upwelling at subduction margins (both compressional and extensional) and where large submarine fans span the continental margin. Sulfur fractionation during bacterial sulfate reduction results in barite with $\delta^{34}S$ values higher than those of seawater (Torres and others, 1996b; Paytan and others, 2002).

Barite accumulations formed at diagenetic fronts will remain small and low grade if the sedimentation rate does not vary and fluids are not advected (Torres and others, 1996a, b). Larger, higher grade barite deposits (max 50 weight percent $BaSO_4$) can form, however, at diagenetic fronts when sedimentation rates decline suddenly or when advection of fluids occurs that contain sulfate from deeper parts of the sedimentary section (Torres and others, 1996b). Ocean-floor barite concretions may have formed where the zone of sulfate reduction occurs immediately beneath the sea floor. Barite concretions collected from near-surface marine mud are porous, spherical to tabular masses with smooth to rough and knobby surfaces (for example, Revelle and Emery, 1951); the deposits are as much as 0.5 m across and contain as much as 80 weight percent $BaSO_4$ mixed with host sediment. Analogous barite concretions in pelagic sedimentary sequences in the geologic record are attributed to diagenetic remobilization of barium and precipitation of barite at the sea-floor/seawater boundary during pauses in sedimentation (Bréhéret and Brumsack, 2000).

Barite may be deposited directly on the sea floor where sulfate-reducing bottom waters are present in the modern oceans. These conditions are restricted to organic-rich ocean basins, such as the Black Sea, the Cariaco Trench, and certain fiords (Falkner and others, 1993), and to continental slopes where intense upwelling occurs (for example, the Peru-Chile margin; Jewell and Stallard, 1991). In local basins within these environments, barite particles from the upper part of the water column are dissolved in reduced bottom waters. Barite subsequently reprecipitates along chemical gradients between the reduced Ba-rich waters and normal seawater. Although this type of deposit appears to be restricted along modern continental margins, it was probably more important in the past when regional and global oceanic anoxia was predominant (Jewell, 2000). A key factor in barite deposition on the sea floor in such an environment is a low input of terrigenous and carbonate sediment; this factor also explains why the accumulation of barite is rare even in the few places where ocean-floor sulfate reduction occurs today. Furthermore, to produce a barite deposit of significant size, the sulfate-reducing bottom waters must remain stable for long periods of time, possibly 10^4–10^5 years.

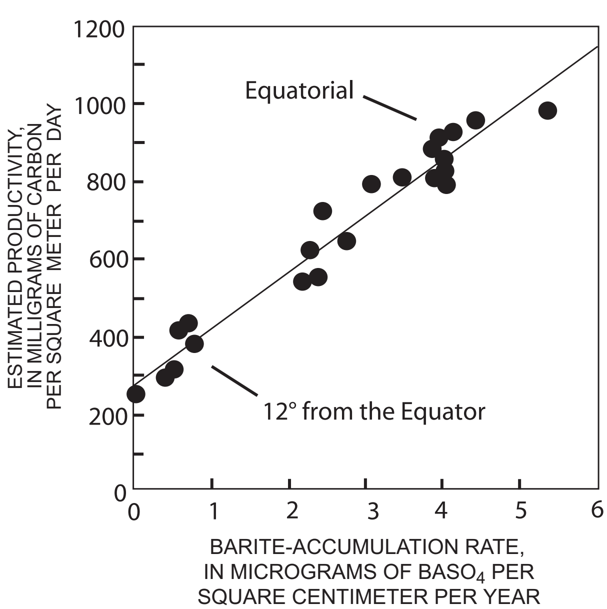

Figure 6.—Estimated productivity (as carbon flux) versus barite-accumulation rate in sediment cores from three north-south transects across the Equator. Data from Paytan and others (1996).

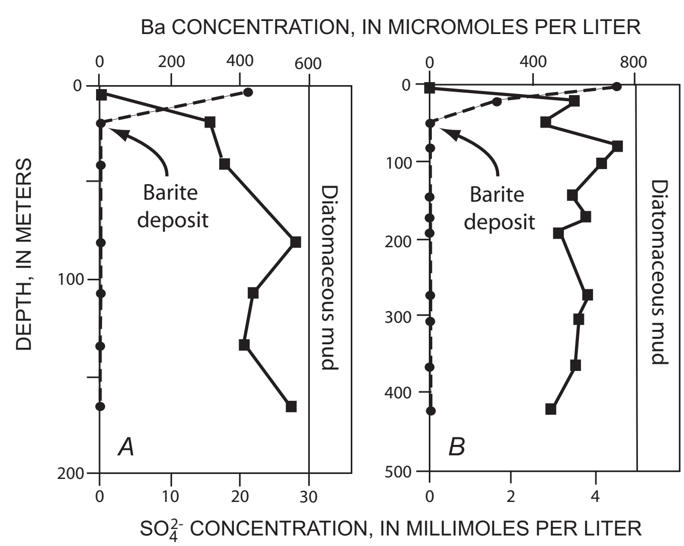

Figure 7.—Pore-water profiles for dissolved barium (squares) and sulfate (dots) in two sediment cores from Ocean Drilling Program sites 685 (*A*) and 688 (*B*) on the Peru continental margin (von Breymann and others, 1990; Torres and others, 1996b). Barite deposits form along diagenetic “fronts” as barium mobilized in zones of sulfate reduction at depth reprecipitates under sulfate-stable, oxic conditions closer to sea floor.

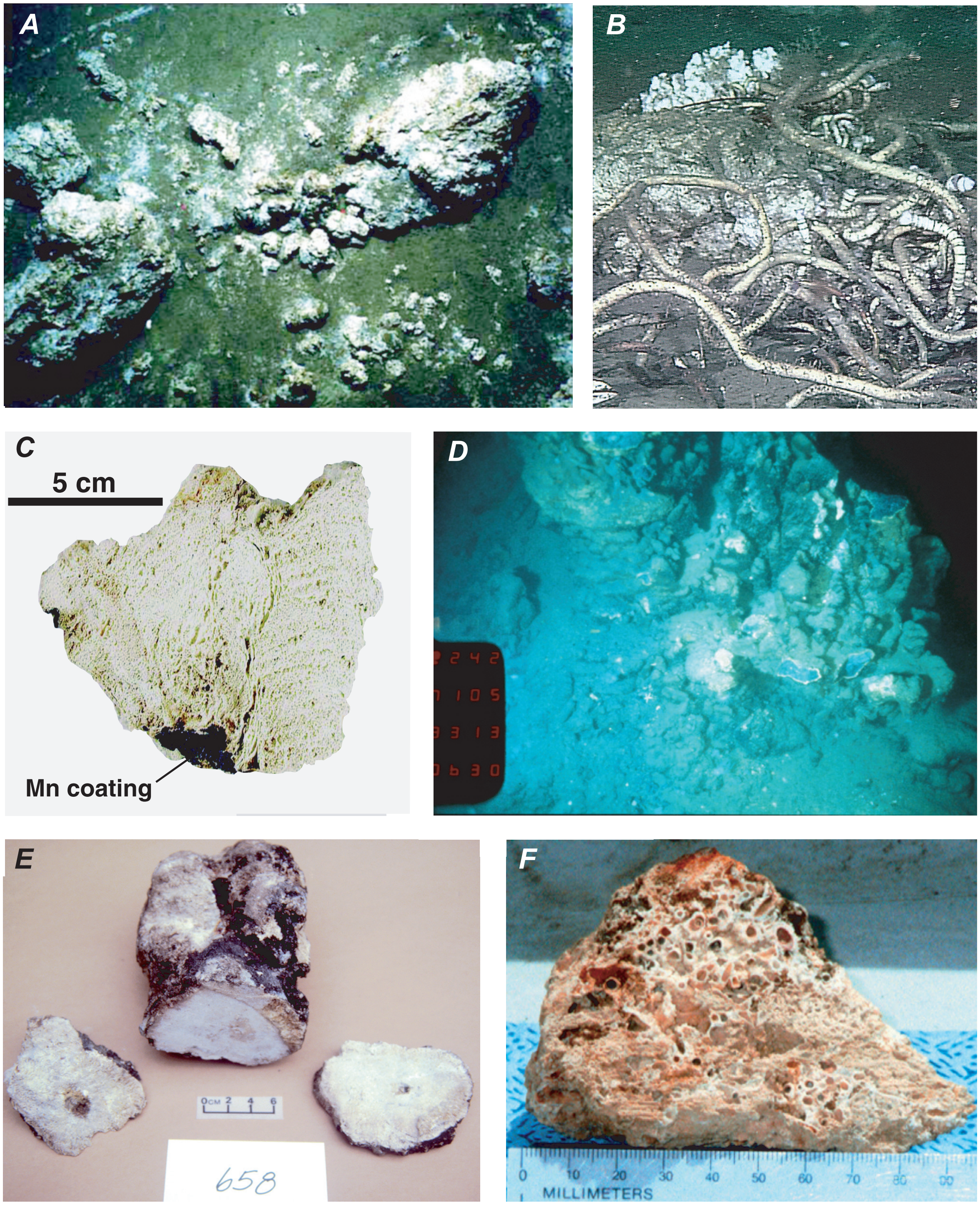

Figure 8.—Massive barite deposits associated with cold seeps and hydrothermal vents. *A*, Mounds of massive porous barite constructed at cold-seep site on unconsolidated sediment in the Derugin Basin, Sea of Okhotsk. Mounds are as much as 10 m high. Field of view, about 1.2 m across. Photograph from Greinert and others (2002). *B*, Small barite mounds covered with vestimentiferan tubeworms at cold seep in Monterey Canyon offshore central California. Field of view, about 0.5 m across. Photograph from Naehr and others (2000). *C*, Porous massive barite with layered appearance and manganese coating from the Sea of Okhotsk. Photograph from Greinert and others (2002). *D*, Knobby massive barite chimneys (with white rims on broken cross sections in upper half of photograph) on platform of massive sulfide on sediment-covered floor of the Escanaba Trough, southern Gorda Ridge. Cluster of barite chimneys is about 1 m high. Photograph from Koski and others (1994). *E*, Nearly pure barite with coating of manganese oxide from chimney in the Escanaba Trough. *F*, Massive barite dredged from the California Continental Borderland contains fossilized worm-tube structures and is interpreted to be hydrothermal in origin (Hein, 2002).

Focused Flow: Cold-Seep Barite Deposits

Massive barite deposits in the form of concretions, crusts, mounds, and chimneys accumulate around cold seeps in various active tectonic settings, including convergent zones, marginal basins, and rifted and strike-slip continental margins (fig. 5; table 1). Massive barite deposits have also been described in the Gulf of Mexico, a passive-margin setting (Fu and others, 1994). This type of diagenetic barite deposit forms during the focused discharge (or, at least, localized flow) of cold Ba-rich fluids onto the ocean floor and is a manifestation of the processes described for the formation of subsurface barite in the previous section. Water depths of known deposits range from several hundred meters to as much as 3,800 m. Relatively large massive barite deposits may result: chimneys and mounds from the southern California margin and the Sea of Okhotsk (fig. 8*A*) are reported to exceed 10 m in height and to occur intermittently along fault scarps for more than 3 km (Lonsdale, 1979; Greinert and others, 2002; Torres and others, 2002). The Sea of Okhotsk cold-seep vent field covers an area of at least 32 km^2 (Greinert and others, 2002). High concentrations of methane and hydrogen sulfide characterize the vent fluids at some ventsites (Barry and others, 1996; Greinert and others, 2002), and cold seeps support unique biologic communities (fig. 8*B*), including vestimentiferan tubeworms, mussels, bryozoans, crinoids, bacterial mats, and other vent-specific faunas (Torres and others, 1996a; Aquilina and others, 1997; Naehr and others, 2000; Greinert and others, 2002). Minute cold-seep barite grains may be transported away from the ventsites by bottom currents and added to sediment distributed over a wide area (Torres and others, 2002).

Cold-seep barite deposits are characteristically porous, with a banded or layered structure indicating multiple episodes or an intermittent style of venting (fig. 8*C*). Although sedimentation rates are commonly high in areas of cold seeps, barite deposits generally are nearly pure (>90 weight percent $BaSO_4$). Minor amounts of pyrite are associated with some deposits (Fu and others, 1994; Greinert and others, 2002). S-isotopic ratios of cold-seep barites generally exceed those for contemporary seawater sulfate. Barites from these environments vary in Sr content (max 11 weight percent) and Sr-isotopic ratio, depending on the rock types leached by circulating fluids. Evidently, the distribution of cold-seep barite mineralization along convergent and transform continental margins is related to fault zones or scarps that crosscut previously buried sedimentary strata. Thus, the low-temperature fluid seeps associated with barite deposition on the Peru convergent margin appear to be controlled by extension-related, low-angle fault scarps that expose deeper, older sedimentary strata within the inner wall of the trench (Torres and others, 1996a). Within the block-faulted transform margin extending offshore southern California, massive barite deposits are forming where permeable strata of the San Clemente Basin are exposed along the San Clemente Fault zone (Torres and others, 2002). Farther north along this transform boundary, the setting of cold seeps and barite deposits in Monterey Canyon suggests that discharge was triggered by slope failure resulting from seismic activity (Naehr and others, 2000). In these occurrences, tectonic events may permit the sudden transfer of Ba-rich fluids and diagenetic fronts to the sediment-water interface.

The thermal history of cold seeps is an unresolved issue. The question arises as to whether cold seeps in some regions may represent the surface manifestations of warmer (hydrothermal) fluids at depth. For example, studies of barite deposits from the same area of the Peru margin have resulted in two interpretations: (1) the deposits are diagenetic and formed during discharge of cold, reduced, Ba-rich fluids (Torres and others, 1996a); or (2) the deposits formed at elevated temperatures (max 80°C) from deeply circulating high-temperature brines (Aquilina and others, 1997). Similarly, barite deposits along the San Clemente Fault in the southern California Continental Borderland have been interpreted as cold-seep deposits on the basis of the absence of temperature anomalies (Torres and others, 1996b), and as hydrothermal deposits on the basis of geologic and heat-flow relations (Lonsdale, 1979). Hein (2002) also suggested a hydrothermal origin for barite deposits recovered in the California Continental Borderland. These divergent interpretations of barite formation suggest that two types of fluid might circulate along fault zones in active-margin settings: (1) relatively shallow formation waters whose composition is controlled by sulfate reduction in the sediment; and (2) warmer, deeply circulating fluids driven by heat sources intersected by faults at depth. Seismic events are likely to promote circulation to greater depths within the crust of fluids that subsequently vent as either warm or cool fluids along the surface expression of the fault. Barite can precipitate from reduced fluids of either type upon mixing with ocean water at or below the sea floor.

Hydrothermal Barite Deposits

Hydrothermal barite deposits are presently forming in various tectonic settings around the Pacific Ocean, including midocean and backarc spreading centers, volcanic arcs, fracture zones, and block-faulted transform continental margins (fig. 5; table 1). Barite-dominant and massive barite deposits are known to occur in several hydrothermally active, sediment-rich environments near continental margins: (1) in the Escanaba Trough, the southernmost spreading axis of the Gorda Ridge; (2) in Guaymas Basin, a spreading segment in the Gulf of California, (3) at several sites in the California Continental Borderland offshore southern California, and (4) in a pullapart basin in the Blanco Fracture Zone, a transform fault that connects the Gorda and Juan de Fuca spreading axes in the northeastern Pacific Ocean. These hydrothermal deposits are related to fluid circulation, volcanism, and emplacement of magma bodies at depth.

In the Escanaba Trough and the Guaymas Basin, massive sulfide and sulfate deposits are present where hydrothermal fluids circulating through several hundred meters of silt and sand turbidites vent onto the sea floor (Koski and others, 1985, 1988; Zierenberg and others, 1993). In each place, the heat source driving fluid circulation is a mafic sill complex emplaced near the base of the sedimentary sequence. Similar to those on sediment-free ocean ridges, active hydrothermal vents at sediment-covered spreading centers are inhabited by vent faunas, including tubeworms. In the Escanaba Trough, massive barite (>50 weight percent $BaSO_4$) occurs as (1) coalesced chimney edifices above sulfide mounds (fig. 8*D*), (2) isolated columnar chimneys on sediment substrate (fig. 8*E*), and (3) crusts on sulfide-dominant mounds. The $BaSO_4$ content of the sulfate-rich hydrothermal deposits varies. Chimneys consist of spongy, nearly monomineralic aggregates of euhedral barite crystals, whereas sinters are mixtures of coarse-grained (tabular crystals, max 2 cm across) barite, pyrrhotite, sphalerite, and galena. Amorphous silica is also present in some crust samples.

Similar barite-rich samples mixed with trace to minor amounts of sulfides have been recovered from active vent fields in the Guaymas Basin (Peter and Scott, 1988, 1991). Most of the barite-rich samples are from chimneys, but a dredged sample of massive granular barite interlayered with compact diatomaceous mud was described by Koski and others (1985). Although the temperature of formation of massive barite deposits has not been determined on the sea floor, O-isotopic data on barite samples from the Guaymas Basin and measurements of sulfate-depositing fluids in the Escanaba Trough suggest a range of about 200–225°C (Koski and others, 1985; Zierenberg and others, 1993).

Within the East Blanco Depression, an extensional basin near the west end of the Blanco Fracture Zone, barite-rich deposits occur on the sediment-covered margins of a pillow-lava dome (Hein and others, 1999). The hydrothermal-vent field, approximately 70 by 90 m, is underlain by volcaniclastic and biosiliceous sediment. Small (<5 m high) mounds and chimneys and thin (<10 cm thick) beds dominated by barite and silica have formed during diffuse flow of low- to intermediate-temperature hydrothermal fluids (<250°C) through the volcanic and sedimentary deposits.

All of the barite-rich deposits in sediment-covered ocean-ridge environments are spatially related to sulfide mineralization. Samples of massive barite from the Escanaba Trough, the Guaymas Basin, and the Blanco Fracture Zone also contain small to significant amounts of Fe, Mn, Zn, Pb, Ag, Au, and SiO_2. Bulk analysis of a sample of nearly pure barite from a chimney in the Escanaba Trough indicates that the barite contains approximately 2.0 weight percent Sr (Koski and others, 1994), whereas the measured Sr content of barite from the Guaymas Basin ranges from 0.7 to 2.6 weight percent (Peter and Scott, 1991). S-isotopic analyses of hydrothermal barite from the Escanaba Trough ($\delta^{34}S$=20.4–22.6 permil) and the Guyamas Basin ($\delta^{34}S$=23.1–29.3 permil) indicate that much of the sulfur in barite is derived from present-day seawater ($\delta^{34}S$~21 permil) during mixing with hydrothermal fluids (Peter and Shanks, 1992; Zierenberg and others, 1993; Paytan and others, 2002). The higher $\delta^{34}S$ values (>23 permil) of hydrothermal barite from the Guaymas Basin, however, indicate some sulfate reduction during the mixing process. This fractionation could occur as isotopically lighter sulfur is preferentially incorporated into sulfide minerals, resulting in ^{34}S-enriched hydrothermal fluid for sulfate precipitation (Peter and Shanks, 1992).

Sr-isotopic data for hydrothermal barite from the Guaymas Basin and Middle Valley, a sediment-covered, hydrothermal-vent field on the northern Juan de Fuca Ridge, were reported by Paytan and others (2002) and Goodfellow and Franklin (1993), respectively. At each site, $^{87}Sr/^{86}Sr$ ratios for barite cluster near 0.706, values that are approximately midway between those of modern seawater (~0.709) and ocean-ridge basalt (~0.703). These ratios are probably derived from interaction between nonradiogenic hydrothermal fluids (ratios close to those of oceanic crust) and underlying terrigenous sediment that contains more radiogenic strontium. The Sr-isotopic ratios of hydrothermal barite are, however, low relative to diagenetic barite, which has ratios closer to that of sulfate in ambient seawater (Paytan and others, 2002).

Another setting for sea-floor hydrothermal barite mineralization is the offshore California Continental Borderland (fig. 5). The basement rocks of this submerged and predominantly transform continental margin consist of Mesozoic and Tertiary volcanic and sedimentary rocks that are overlain by diverse sedimentary strata of marine origin (Vedder, 1987). The ridge-and-basin topography of the borderland resulted from both transtensional and transpressional stresses active during an extended period of wrench faulting from mid-Tertiary time to the present. In places, a combination of extension, block faulting, and high heat flow within the borderland may result in conditions favorable for hydrothermal activity and the formation of barite deposits.

Massive barite nodules and slabs, considered to be hydrothermal in origin, were dredged from the ocean floor offshore California (Revelle and Emery, 1951; Goldberg and others, 1969; Cortecci and Longinelli, 1972). At a site near the base of a scarp within the San Clemente Fault zone, cone and moundlike deposits of massive barite, approximately 2 to 3 m high (and one deposit 10 m high), at apparently active ventsites were observed over a lateral distance of 100 m during submersible investigations (Lonsdale, 1979). Although no temperature data were collected, Lonsdale proposed that the presence of vestimentiferan tubeworms and the milky appearance of bottom water near the deposits are evidence for a hot-spring environment and hydrothermal deposition of barite.

A more extensive, submersible-based study of fluid flow along the San Clemente Fault scarp has called into question the hydrothermal origin of massive barite deposits in the California Continental Borderland (Torres and others, 2002). Torres and others (2002) detected no temperature anomalies in fluids emanating from sand and mud turbidites exposed on the fault scarp and proposed a cold-seep origin for barite in this setting. A possible hydrothermal origin (that is, from heated fluids present at depth) for the San Clemente barite deposits cannot be ruled out solely on the basis of their reported physical and chemical characteristics. The barite samples collected by Lonsdale (1979) and Torres and others (2002) are porous and massive (>92 weight percent $BaSO_4$) and contain as much as 3 weight percent Sr. Their $^{87}Sr/^{86}Sr$ ratios near 0.7084 (Paytan and others, 2002; Torres and others, 2002) reflect previous interaction of the vent fluid with rocks less radiogenic than seawater; $\delta^{34}S$ values of 22.1 to 24.6 permil (Paytan and others, 2002) are similar to those for hydrothermal barite from the Escanaba Trough and the Guaymas Basin. No sulfide mineralization has been reported in association with the barite deposits along the San Clemente Fault zone.

Other massive barite deposits collected from four dredges elsewhere in the California Continental Borderland are texturally and isotopically distinct (Hein, 2002). The samples were recovered from sites along strike-slip and basin-margin faults to 1,800-m depth. The dredged samples include both porous, vuggy aggregates and massive veinlike deposits of nearly pure barite (94–98 weight percent $BaSO_4$); some of the vuggy samples contain embedded worm tubes, as much as 10 cm long (fig. 8*F*). Chemical analyses of the massive barite also show low total rare-earth-element (REE) contents (<45 ppm), Sr contents of as much as 10,000 ppm, and Hg contents of as much as 1 ppm. Shale-normalized REE patterns show light-REE enrichments and large positive Eu anomalies characteristic of marine hydrothermal fluids. $\delta^{34}S$ values range from that of seawater (21 permil) to high values (67.4 permil). High S-isotopic ratios are probably caused by Rayleigh fractionation during closed-system, bacterial sulfate reduction in a methane- or hydrocarbon-rich environment below the sea floor (Hein, 2002). The barite samples with near-seawater $\delta^{34}S$ values are vuggy material believed to have formed on or immediately below the sea floor. The dredged barite vein samples have textures and $\delta^{34}S$ values similar to those of the massive barite veins, as much as 1 m wide, that are exposed in seacliffs of the nearby Palos Verdes headlands (Hein, 2002). The occurrence and composition of this type of massive barite deposit suggests that reduced, Ba-rich hydrothermal fluids may circulate and deposit barite at depth along faults zones. The vast California Continental Borderland is a tectonically complex region that may contain both cold-seep and hydrothermal barite deposits in close proximity to one another.

Modern Marine Barite Deposits as Analogs of Stratiform Barite Deposits in Nevada: A Starting Point

Strict analogs for the Paleozoic stratiform barite deposits of Nevada may be absent in modern ocean basins. The absence of stratification and the relative scarcity of anoxic bottom waters at present preclude the widespread “bathtub ring” deposition of barite where oxic/anoxic seawater boundaries intersect the walls of closed basins or escarpments. In contrast, marine anoxia was intermittently widespread during the Paleozoic, especially during Late Devonian time (for example, Joachimski and Buggisch, 1993; Chen Daizhao and Tucker, 2003), a period during which black shale, stratiform barite, and sediment-hosted Pb-Zn deposits formed along the continental margin of North America (Goodfellow and Jonasson, 1984; Turner, 1992a). Despite this cautionary note, a “modern analogs” approach can provide valuable insights into the origin of stratiform barite deposits in Nevada and elsewhere. This section summarizes relevant observations regarding barite mineralization in tectonic settings of the Pacific Basin and offers suggestions for future research.

Tectonic Setting

Several sediment-rich tectonic settings around the Pacific rim contain massive barite deposits (fig. 5), and one or more of these types of setting may have been present along the western margin of North America during the Paleozoic. Potential tectonic analogs for stratiform barite deposits in a sediment-rich environment include ocean ridges in close proximity to (Escanaba Trough) or intersecting (Guaymas Basin) the continental margin, marginal basins (Sea of Okhotsk), convergent margins (Peru), and transform margins (California Continental Borderland). At present, none of these settings can be ruled out as an analog for ancient stratiform barite of the Roberts Mountains Allochthon, although ocean-ridge settings are less likely because ophiolitic rocks are absent in the allochthon and all known present-day hydrothermal systems at ocean ridges have spatially related sulfide mineralization and mafic igneous rocks related to sea-floor spreading.

Barite deposition in a rifted-continental-margin setting such as the Guaymas Basin and in a marginal-basin setting such as the Sea of Okhotsk is consistent with the models for rifting and barite metallogenesis along continental margins described by Maynard and Okita (1991) and Madrid and others (1992) in which extension develops on a platform of continental crust. Again, however, these contemporary settings may contain igneous-rock suites derived from extensive rifting that are absent in the stratigraphy of the Paleozoic margin assemblages in the Roberts Mountains Allochthon. The convergent-margin setting offshore Peru and the transform-margin setting offshore California may have had tectonic equivalents in the long-lived active margin of western North America during Paleozoic time. Though not fundamentally extensional, these types of plate boundary contain tensional and transtensional zones manifested by block faulting and the creation of pathways for fluid circulation and discharge onto the sea floor.

Other occurrences of marine barite are known in sediment-floored, oceanic tectonic settings not discussed in this chapter—for example, hydrothermal barite in pullapart basins of the Blanco Fracture Zone (fig. 5; Hein and others, 1999) and diagenetic barite on the continental slope of the Gulf of Mexico, a passive-margin site (fig. 5; Fu and others, 1994). As these sites become better known, their significance within a “modern analogs” approach should be evaluated.

Depositional Processes

The accumulation rate of particulate barite from biogenic or hydrothermal sources seems inadequate to form massive deposits in modern ocean basins. The constant rain of barite from the water column is, however, an important component of the barium cycle in the oceans and must contribute to the Ba content of sediment or pore fluids that can be subsequently concentrated by diagenetic or hydrothermal processes.

Massive barite deposits of sufficient size to warrant comparison with Nevada deposits are presently forming in sediment-dominated environments on the ocean floor. Diagenetic and hydrothermal deposit types are characterized by similar sedimentary associations (fine-grained turbidites and biosiliceous sediment) and vent-specific biologic communities. The barite deposits formed along sub-sea-floor “diagenetic fronts” (Torres and others, 1996b) may have analogs in Paleozoic sedimentary sequences but appear to lack the volume and purity of stratiform barites. Similarly, well-studied sediment-hosted hydrothermal barite deposits on ocean ridges lack the continuity and volume of ancient deposits; the modern deposits generally represent sulfate “facies” within larger sulfide-dominant mineral systems. In addition, the less radiogenic $^{87}Sr/^{86}Sr$ ratios of modern deposits on sediment-covered rift zones, a reflection of Sr input from basaltic crustal sources, contrasts with the Sr-isotopic ratios of ancient deposits.

Cold-seep barite deposits appear to have attributes (size, distribution along fault scarps), mineralogy ($BaSO_4$ content, SiO_2 content), and isotopic characteristics (S, Sr) that, in total, more closely resemble those of the stratiform deposits of Nevada. The siliceous and organic-rich sediment related to high-productivity zones in the Sea of Okhotsk, along the Peru margin, and in the California Continental Borderland is reminiscent of the organic-rich chert and shale associated with barite deposits in the Roberts Mountains Allochthon. These high-productivity zones represent a favorable environment for bacterially mediated sulfate reduction leading to the ^{34}S-enriched isotopic signature of diagenetic barite.

Working Hypothesis and Avenues for Future Research

A consideration of the stratiform barite deposits of Nevada and the submarine barite deposits along modern continental margins yields a working hypothesis for the most suitable modern analog. Our study suggests that cold-seep mineralization in tensional environments along modern transform continental margins (or, possibly, marginal basins) represents a process and setting most likely to accumulate large deposits comparable to the stratiform barite deposits of Nevada. Hydrothermal systems can also accumulate high-grade barite, but the small scale of such deposits presently known on the modern sea floor and the paucity of sulfide mineralization in the ancient deposits are problematic. At this point, neither the presence of vent faunas nor S-isotopic data for barite permit discrimination between a diagenetic or hydrothermal origin. Interpretation of the genesis of barite deposits may be complicated by the juxtaposition of hydrothermal and diagenetic deposits in the same tectonic setting (for example, the California Continental Borderland).

This chapter is based on a review of available data; clearly, acquisition of new data is needed to facilitate comparisons between modern and ancient barite deposits and among deposit types, to identify the most likely analogs in the modern ocean, and to apply what is known about these analogs to the construction of better deposit models for stratiform barite. We note that two recent parallel studies have resulted in similar conclusions regarding (1) cold-seep environments as likely depositional analogs (Torres and others, 2003) and (2) the California Continental Borderland as a probable tectonic analog (Clark and others, 2004) for Nevada barite deposits. Suggested areas of additional research include:

1. Detailed geochemical, isotopic, and paleontologic studies of ancient stratiform barite deposits to identify additional genetic indicators. In addition, further regional site-specific petrologic studies in the Roberts Mountains Allochthon are needed to better understand the tectonic framework for sedimentary rocks and contained barite deposits.
2. Additional detailed investigations of fluid flow and mineralization along modern transtensional continental margins (including marginal basins) to elucidate ore-forming processes. These investigations should be conducted in conjunction with future submersible and drilling programs in the ocean basins.
3. Additional analytical data for both modern and ancient barite deposits to augment the data listed in table 1, including trace elements, REEs, and Pb, Sr, C, and O isotopes for barite and associated minerals. Geochemical and isotopic characterization of modern marine barite deposits by Paytan and others (2002) indicates the value of this approach.
4. Further studies of the fluid chemistry of cold seeps to determine whether hydrothermal processes contribute to mass flux at the ventsites.

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